

Chapter 10

Climate Change Impacts on Rice Farming Systems in Northwestern Sri Lanka

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Introduction

Sri Lanka hosts a population of 21 million people in a relatively small area of 65,610 km² (Fig. 1). Relatively high rainfall (1830 mm annually) and an equable temperature regime along with fertile soils have enabled the adequate provision of food and water to its people. Although agricultural production has increased over the last century, the population has been rising, reaching 21 million in 2011 from 14.7 million in 1980 (Department of Census and Statistics, 2012b). While advances

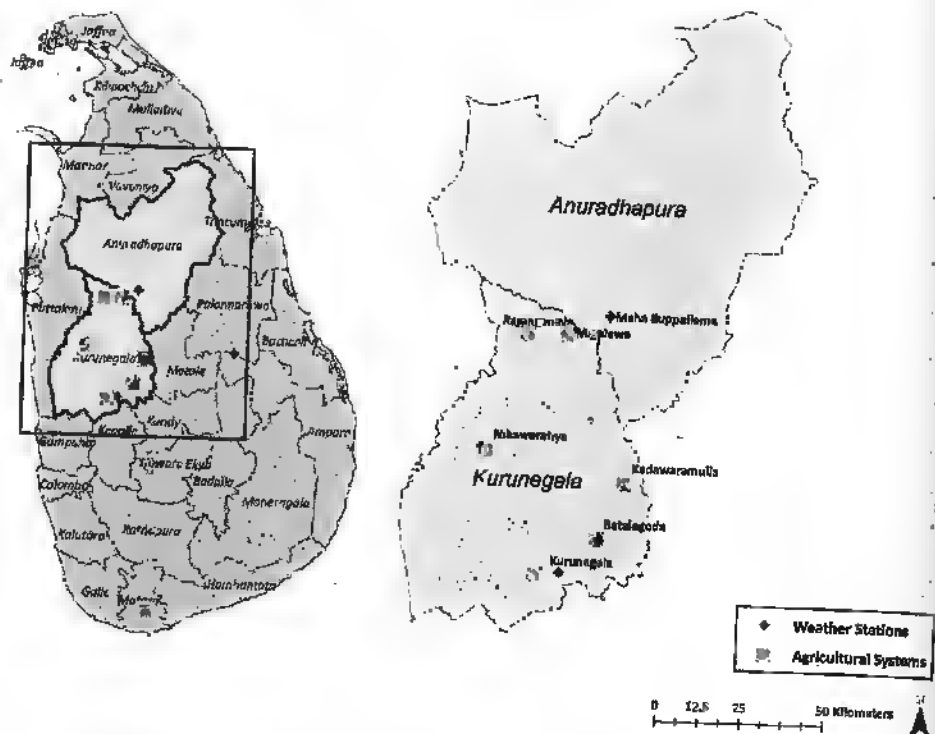


Fig. 1. Sri Lanka and the northwestern study region, with meteorological stations, agricultural research sites, and farming systems.

in agricultural research have been noteworthy, the challenge of securing food supply has been exacerbated by conversion of agricultural lands, internal conflict, limited technological inputs, and periodic shortages of water that constrain yield.

Agriculture accounted for 11.1% of the national gross domestic product (GDP) in 2012, while providing direct employment to 31% of the labor force (Central Bank of Sri Lanka, 2013), indirectly contributing to the livelihoods of up to 70% of the population. Among the crops that account for 78% of the agricultural GDP are rice, tea, and coconut crops which contribute 13.4%, 10.1%, and 10.9% to the agricultural GDP, respectively. Rice is the principal food crop and is grown over approximately 6,135 km² in the primary cropping season of Maha (October to March), with cultivation over about half that extent in the secondary seasons of Yala (late April to early September), depending largely on the availability of water. Around 879,000 farmer families are engaged in rice cultivation (20% of the population), providing livelihoods for up to 32% of the population (Department of Census and Statistics of Sri Lanka, 2012a). The country has become nearly self-sufficient in rice production (Department of Agriculture, 2009).

Sri Lanka has achieved tremendous progress since 1950 in crop production and food availability (Department of Agriculture, 2010; Ministry of Agriculture and Agrarian Services, 2008). Yields grew at an impressive rate until leveling off in the mid-eighties (Department of Agriculture, 2009). Sri Lanka's population is anticipated to continue to grow in the coming decades (Department of Census and Statistics, 2012a), creating an ever-greater demand for food security on the household, sub-district, regional, and national scales (Sangakkara and Nissanka, 2008).

The agricultural sector in Sri Lanka is vulnerable to climate shocks (Yahiya *et al.*, 2011; Zubair, 2002). An unusual succession of droughts and floods from 2008 to 2014 has led to both booms and busts in agricultural production, which were reflected in food prices (Gadgil *et al.*, 2011; Zubair, 2005). In both instances, the majority of farmers and consumers were adversely affected. The cultivation of some of the other crops (such as onions, chilies, and vegetables) has become more economically viable especially with the constraint of water. A typical small-scale farming system is represented schematically in Fig. 2. The household unit includes a home garden, other field crops, and livestock.

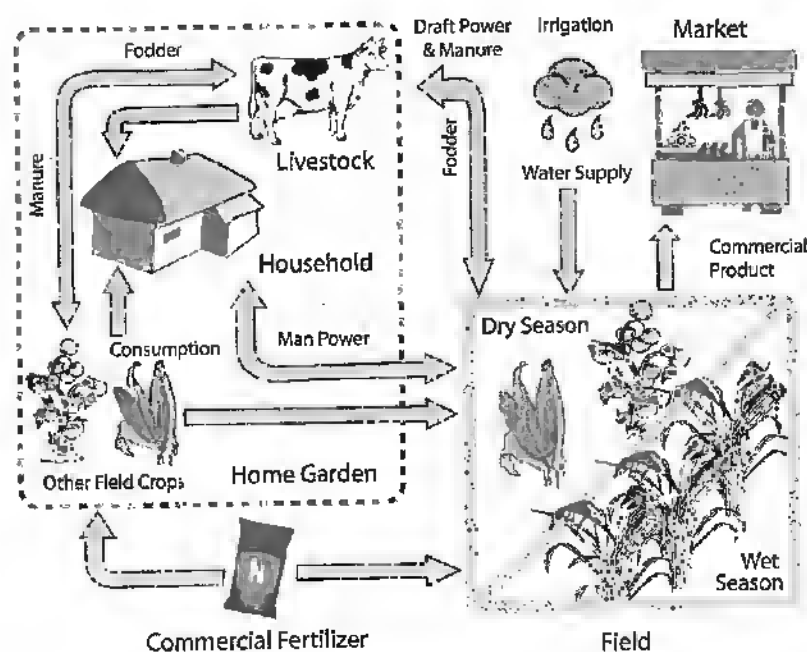


Fig. 2. A schematic of the rice-dominated agricultural system in this region.

At present, the rice-farming systems are under stress due to inadequate returns for the farmers and difficulty in coping with shocks due to climate, pests and diseases, and prices for produce. There are government price-support mechanisms, fertilizer-subsidy schemes, and crop insurance schemes, but the levels of the supports are modest and often do not effectively reach the farmers.

Climate change could compound this situation further if, as projected for South Asia, there is greater tendency for increased temperatures and extreme weather. IPCC (2013) projected that the mean annual temperature shall rise by between 0.5–4°C for the South Asian region for the 2081–2100 period in comparison with 1986–2005, with the lower rise for the lower (RCP2.6) greenhouse-gas-concentration pathways and the higher rise for RCP8.5 (Moss *et al.*, 2010). The precipitation is also expected to increase in South Asia (IPCC, 2013) by 0.5 to 4 mm/day on average, with lower values for the RCP2.6 scenario and higher values for the RCP8.5 scenario. While prior assessments have shown consistency across global climate models for temperature projections, there is greater variability among the projections in regard to precipitation (Eriyagama and Smakhtin, 2010; Mahanama and Zubair, 2011). There have been recent modest drying trends in parts of Sri Lanka (Ministry of Environment, 2000, 2010; Zubair *et al.*, 2006). Thus it is particularly important to assess climate change projections for precipitation in Sri Lanka, given that annual rainfall has high spatial variability (ranging from 500 mm to 5500 mm); (see, e.g., Lyon *et al.*, 2009). Agricultural water demands have been projected to rise, leaving the northwest Sri Lanka under “Moderate to Severe” scarcity by 2025 depending on water-use practices (Amarasinghe *et al.*, 1999).

Field trials (De Costa *et al.*, 2007; Weerakoon *et al.*, 2005) and crop modeling research (Dbarmaratna *et al.*, 2014) suggest that yields in the subhumid regions of Sri Lanka, such as the northwest, are likely to be impacted adversely if temperature increases, although yields could increase if rainfall and CO₂ concentrations rise. The level of sensitivity to temperature is likely to be critical as the rice crop approaches its highest level of temperature tolerance (Weerakoon *et al.*, 2005). Rising sea levels can also affect some of the rice-growing areas if it leads to salination (Ministry of Environment, 2010). There have been a few assessments of the economic impacts of climate change on agriculture in Sri Lanka that link climate projections to yield and estimated economic output (Seo *et al.*, 2005; Kurukulasuriya *et al.*, 2007). These projections relied on statistical relationships between climate and yield projections and pointed to negative economic impacts due to rise in temperature and positive impacts due to rise in rainfall, as found in projections from five GCMs. The work on climate, crop, and economic assessment so far has been limited with regard to model integration, model intercomparisons, and the characterization of uncertainties.

There is a millennium-long history of adaptation (spatially and seasonally) to climate variability across the island through choice of climatically and environmentally appropriate varieties, tailoring of planting season by region, development of appropriate irrigation infrastructure, and social and trade arrangements to suit communal agricultural practices (Zubair, 2005). These adaptation methods afford some potential for coping with future climate change, but they may not be capable of dealing with unprecedented changes. There is an ongoing program of rice varietal improvement at the Department of Agriculture and universities which historically have an excellent track record.

The AgMIP (Rosenzweig *et al.*, 2012) regional assessment in Sri Lanka addresses these issues by generating future climate projections and using them to drive crop models that feed into integrated climate-crop-economic models that in turn quantify climate impacts on livelihoods and poverty. We also test adaptation strategies in this modeling framework under future representative agricultural pathways (RAPs).

Interactions with Stakeholders, Adaptation Options, and Agricultural Pathways

Government policymakers, water-resource managers, local government officials, and farmers have highlighted the need for reliable climate change information, the need to orient research to address the questions they face for allocating resources, and the need for researchers to stay engaged and to disseminate learning.

Interactions with stakeholders

Personnel from the Department of Agriculture involved with the AgMIP regional integrated assessment have solicited advice at departmental meetings and are in a position to contribute to departmental policy.

We have reviewed climate risk information needs with personnel of the Mahaweli Authority of Sri Lanka (MASL), which is a large river basin management agency that provides services for the farmers in its domain (including water distribution, seed distribution, agricultural extension, community development, and enterprise development). The MASL coordinates national water management, to which effort the project investigators have provided a weekly climate advisory.

The University of Ruhuna researchers are engaged in a project to undertake multi-sectoral, multi-institutional, community-based climate risk management in the Nilwala river basin in the south (Zubair *et al.*, 2014). The perspectives of farmers and officials in this region regarding climate change and adaptation were solicited.

We also interacted with bulk purchasers of rice husks for energy conversion and rice for export as regards their needs for climate based predictions and projections of rice harvests (Zubair et al., 2014).

Key decisions for national policymaking

Among the key decisions for rice farming systems for the decades ahead are development of national plans for agriculture, land and water resources, food security, environment, poverty alleviation, and guidance for long-term infrastructural investments.

Potential adaptation strategies

Based on a review of national policy documents related to agriculture and climate change adaptation (e.g., Ministry of Agricultural Development and Agrarian Services, 2007; Ministry of Environment, 2010), assessments of researchers, and interactions with stakeholders including farmers, the following adaptation strategies have been proposed: (1) investment in research, innovation, and technology diffusion; (2) promotion of better-adapted cultivation practices and adaptive management of farming systems; (3) risk management of shocks to the farm economy due to climate, pest, diseases, and market volatility; (4) decrease in food losses from farm gate to consumption; and (5) restructuring of policies on farming subsidies, price supports, crop insurance, and trading policies. These policy interventions can be sharpened and prioritized with better information on climate change and its impacts.

Farmer perceptions of climate change and potential adaption

Researchers solicited farmer perspectives in the Kurunegala (Migalewa, Kadawaramulla), Ampara (Mahawanawella), and Matara districts (Nilwala Basin) (Fig. 1) — details in Zubair et al. (2014). Farmers in Migalewa perceive the following as major climate-related problems:

- Climate: (1) Changes in total seasonal rainfall; (2) changes in starting date and duration (number of days) of growing season; (3) increase in occurrence of drought; (4) more frequent drought following intense rainfall.
- Crops: Increase in occurrence of crop damages and reduction in harvest due to drought.
- Water supply: (1) drop of groundwater level; (2) decrease of water supply for cultivation; (3) reduction in the duration of water supply for cultivation.
- Pest and diseases: (1) appearance of new diseases and pest attacks.

While issues related to flooding and deforestation were not discounted, these were not a priority for the farmers. They identified the following as practical adaptation options: (1) application of organic fertilizers, insecticides, and herbicides; (2) use of drought-tolerant varieties and shorter-duration crops; (3) change of seasons for cultivation and of planting dates; (4) crop diversification and intercropping; (5) rain-water harvesting; and (6) diversification of livelihoods and non-agricultural income sources. Farmers did not think it was practical either to undertake drip irrigation or energy-intensive cultivation.

Constructing Representative Agricultural Pathways

Representative agricultural pathways (RAPs) ensemble an overall narrative description of a plausible future development pathway and key variables with qualitative storylines and quantitative trends — consistent with higher level pathways such as SSPs and RAPs developed by the AgMIP global modeling group (Rosenzweig, *et al.*, 2013a) described further in Part 1, Chapter 5 in this volume.

RAPs were constructed in consultation with researchers and officials, officers of the Department of Agriculture, and the other departments based on literature from several government agencies, consultation meetings, and iterative review. The salient projected changes that are most likely in the coming decades are:

- The current trend of economic growth is projected to continue.
- Population growth rate remains low and urban population increases while rural household size decreases, and farm size declines.
- Rice productivity shall be adversely affected due to deterioration of soil fertility, extreme weather events, climate change, and phasing out of fertilizer subsidies (without adaptation).
- Transportation infrastructure improves and trade policy encourages exports and imposes high taxes on imports of food that can be grown locally.
- Technology developments in the rice sector with high-yielding, drought- and flood-tolerant cultivars, and improved crop management practices shall improve rice productivity.

Summary Narrative of the Adopted RAP

Best practices are implemented in a context of economic growth, low population growth, urbanization, and increasing productivity in the rice sector in a business-as-usual scenario. The government invests more in agriculture to improve food security through self-sufficiency in rice within a framework that promotes the ability of the rice sector to cope with impacts of a variable climate. This is done in a

context of deteriorating biophysical conditions and shortage of labor with decreasing household and farm sizes. Research and development on high-yielding, drought- and flood-tolerant varieties are introduced with enhanced crop management practices to mitigate climate change impacts on rice productivity. The use of organic fertilizers will be promoted while reducing the application of inorganic fertilizers, by phasing out past subsidy schemes. The irrigation/water management system continues to be adapted so as to cope with drought conditions, even while water available for agriculture is reduced.

An associated DevRAP matrix (Table 1) was developed based on the AgMIP methodology (see Part 1, Chapter 5 in this volume) detailing the biophysical, institutional/policy, socio-economic, and technological parameters that characterize the future biophysical and socio-economic conditions, including the likely direction and

Table 1. The variables or indicators which were quantified in the DevRAP matrix were classified under biophysical, institutional and policy, technological, and socio-economic categories. The magnitude of the anticipated change with increasing time is represented by the slope of the arrow.

Category	Variable/Indicator	Direction and magnitude of change				
BioPhysical	Rice land degradation	↗				
	Water availability	↘				
	Land use	↘				
Institutional/Policy	Input subsidies (fertilizer)	↘				
	Infrastructure/rural/agricultural access roads/irrigation	→				
	Trade policy/taxes on import and export	↗				
	Investment on R and D	→				
Socio-Economic	Labor availability	↘				
	Off farm employment	↗				
	Cost of Production	↗				
	Farm Size	→				
	HH size	→				
Technology	Improved rice cultivar productivity trends	↗				
	Improved management practices	↗				
	Mechanization for cultivation	→				
Unchanged	Low increase	Low-Medium increase	High increase	Low decrease	Low-Medium decrease	High decrease
→	→	↗	↗	→	↘	↘

d in the DevRAP
policy, technologi-
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[illegible]

In relation to the biophysical parameters, temperature changes and land degradation were identified as important, while there was low confidence on the precipitation increases that have been projected in the past. Among the socio-economic parameters, the current and likely future dearth of agricultural labor and outward migration for employment were identified as important parameters. Among the institutional and policy changes, a reduction in fertilizer subsidies is anticipated, even while investment in the agriculture sector could increase and the coordination among different agencies dealing with agriculture could improve. In the technological realm, it is anticipated with high confidence that farmers will have improved access to information on markets, weather, and climate in the future and that improved varieties of rice will become available.

Sri Lanka has rich archives of agronomic data (Pain, 1986; Wickremasinghe, 2006), which have led to (1) long-term studies on crops, including detailed field trials and coordinated rice trials; (2) long-term climate data at fine resolution (e.g., Zuhair, 2004); (3) household-level survey data and aggregated data for economic analysis and (4) data from rice research stations and university research programs.

Station data

Meteorological data for Batalagoda (7.51° N, 80°43' E), Maha Illuppallama (8°10' N, 80°45' E), and Maho (7°82' N, 80°27' E) of precipitation, maximum temperature, and minimum temperature were obtained for the period of 1980–2012. Daily rainfall, minimum and maximum temperature, atmospheric pressure, and sunshine hours are recorded at these stations (Zubair *et al.*, 2014).

The AgMERRA data produced by the AgMIP Climate Team (Ruane *et al.*, 2014) from the MERRA data (Rienecker *et al.*, 2011) were used for gap-filling and for variables that were not available, after applying necessary bias-corrections.

The data from the 20 GCMs in the CMIP5 archive (Taylor *et al.*, 2012) were used for projecting future climate. Analysis was restricted to five GCMs (CCSM4,

GFDL-ESM2M, HadGEM2-ES, MIROC5, and MPI-ESM-MR) that were identified by AgMIP as relatively skillful in reproducing the climate over South Asia by AgMIP.

Crop Data

Aggregate historical data on area of cultivation, production, and yield are estimated collectively by several government agencies.

Rice experimental trials

Experimental data for rice trials are available from the Department of Agriculture (Batalagoda, Maha Illupallama, and other field stations). Calibrations were carried out on the following varieties of data in wide spread use in the region — Bg300 (three months duration), At308 (three months), Bg357 (three-and-a-half months), Bg358 (three-and-a-half months), and Bg379-2 (four to four-and-a-half months). Further details are available in the chapters on calibration in Zubair *et al.* (2014) including for other varieties (Bg250, Bg304, Bg307, Bg94-1).

Data from (1) detailed field trials and (2) Coordinated Rice Variety Trials (CRVTs), were used for calibration and evaluation of models. These detailed experiments, conducted at the Rice Research and Development Institute (RRDI) of Sri Lanka at Batalagoda, from 2001–2010 in the major (Maha) and minor (Yala) growing seasons with two nitrogen fertilizer levels. CRVTs were conducted at two different agroecological regions of RRDI and FCRDI (Field Crop Research and Development Institute (FCRDI) at Maha Illupallama), during the two growing seasons from 2000 to 2008.

The size of the experimental plot was 18 m² (6 m × 3 m). Recommended standard procedures by the Department of Agriculture (DOA) were adapted for rice crop management. Irrigation was provided, then the land was ploughed, crop residues of the previous season were incorporated three weeks before planting, and the soil was puddled continuously with subsequent ploughing/harrowing actions undertaken at least twice to make the fields weed-free and level before planting.

The crop was established by broadcasting pre-germinated seeds (direct seeding at a rate of around 350 plants/m²). Irrigation water was provided as required and maintained at a standing water level of about 25 mm starting from one week after emergence until grain-filling was completed.

Fertilizer application was carried out as recommended by the DOA. Split application was practiced as at planting, first top dressing (two weeks after planting), second top dressing (five weeks after planting), third top dressing (seven weeks after planting) for three-month varieties, and additional application of N at booting stage for three-and-a-half and four month varieties. Medium fertilizer treatment represents

the DOA recommended fertilizer levels. Continuous monitoring of pest and disease outbreaks was undertaken and appropriate control measures were applied whenever necessary.

For the detailed experiments, growth and development parameters (plant height, leaf area, and tiller count) were recorded at regular intervals, along with time taken to panicle initiation, anthesis and maturity stages. Yield and yield components were measured at maturity. For CRVT experiments, time taken to heading and harvesting stages, and yield measurements were recorded.

Data for Integrated Assessment

Researcher-conducted surveys of farming systems are available for a cross-section of farmers in selected locales in the Kurunegala district (Fig. 1). These locales are referred to as Set 1 (Nikaweratiya, Rajangane, and Batalagoda) and Set 2 (Kadawaramulla, Migalewa) and details are provided in Zubair *et al.* (2014). All of the locations except Kadawaramulla practice cultivation in the minor Yala season. In Kadawaramulla there is a system of irrigation in alternate years for Yala for each bank of the feeder irrigation canal. Including Kadawaramulla ensures that we capture practices that are representative of the entire district. Although we have conducted surveys for two successive Yala seasons for Kadawaramulla, the year it received irrigation coincided with a drought that devastated the rice crop during the Yala season. So for Set 2, to be able to represent both seasons, we report here on the results for Migalewa while detailed results for Kadawaramulla are not shown here, but are included in Zubair *et al.* (2014) and in Hcrath *et al.* (2013).

Soil and climate files were developed for the respective sites based on the recorded information (Mapa *et al.*, 2005). Additional soil testing was undertaken for Kadawaramulla and Migalewa (Zubair *et al.*, 2014). Crop management practices for farmer fields were estimated based on the farmer-survey information and standard practices.

Methods of Study

Climate

The work followed methods outlined in the AgMIP Handbook (Rosenzweig *et al.*, 2013a) and described further in Part 1, Chapter 3 in this volume.

Quality control

Inconsistent data entries were identified and removed. Neighboring station data were compared in cases of unusual observations. The solar radiation data were taken from

AgMERRA datasets developed by the AgMIP climate team (Ruane *et al.*, 2014) and compared with estimations from sunshine hours based on a previously calibrated algorithm (Samuel, 1991).

Missing values of variables and gaps from data removed for quality control were filled in. If the gap was less than two days, it was filled based on the values on both sides of the gap and after cross-checking with observed values of neighboring stations for validation in the case of temperature. Other gaps of data (more than two days) were filled by using the AgMERRA dataset prepared by the AgMIP climate team with bias-correction.

In instances where the farm locations were not close to the meteorological stations, a method of extrapolation developed by the AgMIP Climate Team based on the high-resolution monthly spatial climatologies developed by WorldClim was used.

Mid-20th century projections

The work reported here focused on GCM-based estimates for the mid-20th century (2040–2070) under a high-emission-concentration pathway (RCP8.5) (Moss *et al.*, 2010; Taylor *et al.*, 2012). The results from the following five GCMs were used for some of the more detailed analysis as they represent the South Asian region better: CCSM4, GFDL-ESM2M, HadGEM2-ES, MIROC5, and MPI-ESM-MR (labeled as E, I, K, O, and R respectively). The methodology for downscaling the climate projections to each station was based on the “delta method” (Wilby *et al.*, 2004). The implementation is described in detail in Part 1, Chapter 3 in this volume. Time series at individual stations were created by modifying the meteorological station data with mean monthly spatial differences provided by the WorldClim dataset (Hijmans *et al.*, 2005).

The significance of future change in this average temperature precipitation and of all 20 GCMs were tested based on whether there was a change of two standard deviations of yearly variation (see Part 1, Chapter 3 in this volume).

Crop Model Calibration and Simulations

Calibration

Calibration of DSSAT-CERES-Rice version 4.5 (Jones *et al.* 2003), and APSIM-ORYZA version 7.5 (Keating *et al.*, 2003) crop models was undertaken for the commonly used varieties of rice in Sri Lanka for which experimental data were available (Bg 250, Bg 300, Bg 357, Bg 358, Bg 379-2, At 307, and At 308). These data are based at Batalagoda and Maha Ilupallama, along with the data from the national CRVT for the same locations.

Table 2. Genetic coefficients generated for DSSAT-CERES rice crop model for four cultivars.

	P1	P2R	P5	P2O	G1	G2	G3	G4
Bg 300	407.9	134.7	396.2	12.6	50.7	0.026	0.95	1.1
Bg 357	382	122.5	393.8	11.5	55.5	0.025	0.95	1.23
Bg 358	435.6	72.5	500.1	10.7	50.3	0.019	0.69	1.1
At 308	400.8	50.3	400.7	12	68.5	0.019	1	1.2
Bg 379-2	662.9	140.9	437.1	10.8	58.9	0.03	0.5	1.16

DSSAT CERES-Rice calibration

Detailed experiments and CRVT from two experimental sites at Batalagoda and Mahailuppallama were used for generalized likelihood uncertainty estimation (GLUE) runs, initially only for phenology. Then GLUE-estimated phenology was fixed for the estimation of growth parameters (G1, G2, G3, G4) by using measured growth variables in detailed experiments. The grain size (G2) was calculated for selected varieties based on historical data and fixed for the variety. Therefore, only G1, G3, and G4 were estimated from GLUE runs of detailed experiments. The crop model simulations were evaluated by using model efficiency criteria for leaf-area index (LAI), tops weight, tiller number, and yield predictions for detailed experiments, and yield only for CRVTs. The genetic coefficients obtained are provided in Table 2.

APSIM calibration

The same dataset used for DSSAT calibration was used for APSIM calibration. The APSIM-ORYZA model parameters of rice according to different growing stages were considered for the calibration of the respective varieties; these include two photoperiod-sensitive stages and two growth parameters. Developmental stages of the crop model are:

- | | |
|---|--------------------------------------|
| 1. DVJR; Development stage in juvenile phase | } Photoperiod-sensitive phase |
| 2. DVRI; Development stage in photoperiod-sensitive phase | |
| 3. DVRP; Development rate in panicle development | } Photoperiod-insensitive parameters |
| 4. DVRR; Development rate in reproductive phase | |

The fixed values of DVS at important growth stages in APSIM are 0 (at sowing), 0.65 (at panicle initiation), 1 (at flowering), and 2 (at maturity).

Developmental rate parameters (DVS) were calculated by using growing degree days (GDD). GDD were calculated by using T_{max} , T_{min} , and base temperature (T_b),

Table 3. Genetic coefficients generated for APSIM-Oryza rice crop model for four cultivars

Model parameter	Bg 300		Bg 357		Bg 358		Bg 379-2
	Yala	Maha	Yala	Maha	Yala	Maha	Yala
DVRJ	0.001071	0.001071	0.000878	0.000878	0.000869	0.000869	0.001037
DVRI	0.000853	0.001071	0.000737	0.000878	0.000721	0.000869	0.000285
DVRP	0.000646	0.000646	0.000636	0.000636	0.000641	0.000641	0.000643
DVRR	0.001755	0.001755	0.001729	0.001729	0.001871	0.001871	0.001869
MOPP	13	13	13	13	13	13	11.5

i.e., 8°C. GDD for phenological events were calculated based on the ORYZA-2000 model. The parameters estimated for APSIM inputs are given in Table 3.

DSSAT-CERES and APSIM-ORYZA crop model simulations

DSSAT-CERES and APSIM-ORYZA simulations were undertaken based on the farmer surveys identified as Set 1 and Set 2. These simulations were undertaken with consistent genetic coefficients, consistent choices for management but differentiated by the details of the farm surveys and the soil and weather for Set 1 and Set 2.

The "IT tools" developed by AgMIP were used to undertake the large number of simulations required in a hatch mode. The weather, soil, fertilizer, water, and crop management data were incorporated into the input files (i.e., field overlay file, survey data file, and seasonal strategy file) that were prepared for the QUADUI AgMIP IT tool (Rosenzweig *et al.*, 2013a). This enabled the generation of DOME and ACMO files for input into the crop simulations and integrated assessments.

Farm-survey data were used in order to match crop management (Hoogenboom *et al.*, 2010), i.e., planting, harvesting, application of inorganic fertilizer, irrigation, and applications of crop residues and organic manure.

Yields for the "current year" (2012/2013 for Set 1), were simulated for individual farm fields. For Set 2, the current year was September 2011 to August 2012 for Kadawaramulla and September 2012 to August 2013 for Migalewa.

Using these simulated results for the "matched data case" (Rosenzweig *et al.*, 2013a) were obtained where the models use weather, soil, and management for each field to simulate production matched with observed yields for each field. Yields for the future periods (2040–2069) were obtained by using the corresponding climate change scenarios derived from global climate models and observed weather data (Rosenzweig *et al.*, 2013a, 2013b).

In simulating the future period, automatic planting was set within an interval of time with conditions for soil water content (i.e., target rainfall accumulation) specified at 20 mm. The harvesting option was set as "when the crop is mature".

sp model for four cultivars.

	Bg 358	Bg 379-2
la	Maha	Yala
869	0.000869	0.001037
721	0.000869	0.000285
641	0.000641	0.000643
871	0.001871	0.001869
13	13	11.5

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rainfall accumulation)
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In simulating the future period for Migalewa and Kadawaramulla, automatic planting was set for one-day duration for the planting window and for soil water content specified at 150 mm.

Integrated Assessment

We used the Tradeoff Analysis Model for Multi-dimensional Impact Assessment (TOA-MD) economic model, which is a multi-dimensional impact assessment program that utilizes statistics of farm characteristics (means, standard deviations, coefficients of variation) to simulate the impacts of environmental changes on economic conditions (Antle, 2011; Antle and Valdivia, 2006). In this study we use it to assess climate change impacts on socio-economic aspects of farming systems with the intent of providing support for informed policymaking. The model could be used in the future for prospective evaluation of technology adoption and technology impact assessment, payments for ecosystem services and environmental change impact and adaptation.

The TOA-MD analysis was undertaken for a population of heterogeneous farms under one stratum with one production activity of growing rice. These methods were followed to answer the following three "core climate impact questions" as posed by AgMIP (Rosenzweig *et al.*, 2013a).

1. What is the sensitivity of current agricultural production systems to climate change?
This seeks to address the impact of climate change on the current production.
2. What is the impact of climate change on future agricultural production systems?
This seeks to address the impact of climate change on the future production system. Technological and other developments in the agricultural sector may alter the current production system in the future. Hence vulnerability to climate change may be dissimilar to the case of the current production system, which is described in the Question 1 simulations.
3. What are the benefits of climate change adaptations?
This line of inquiry seeks to assess the advantages of adaptation strategies in abating deleterious climate change impacts on the future rice-production system. While we have undertaken work on adaptation, it shall be reported in the future.

While TOA-MD analysis was initiated for all of the farming systems, in this chapter results are presented only for Migalewa.

In setting up the TOA-MD model there was one key assumption. The farmer surveys in Migalewa were undertaken separately for each of the two seasons in the same small region. The populations of farmers for each season have similar household economics and use similar crop management practices. In fact, nine

Table 4. Farm sizes and household sizes for the two surveys taken during the Yala and Maha seasons conducted at Migalewa.

Season	Sample size	Farm size	CV of farm size	HH size	CV of HH
Maha	31	0.89	22.16	4.16	29.17
Yala	31	0.82	33.95	4.45	28.91

of the 38 farmers overlapped. For the TOA-MD analysis, these two populations were assumed to provide statistics that are representative of the region for each season. Farm size and household size for the farmers are very close (Table 4) and these farmers were all chosen within an "irrigation block" of the regional office for System H of the Mahaweli River Basin Authority. Thus these two sets of farmers should have similar practices, market conditions, technical resources and settlement histories (Raby and Merrey, 1989). Based on this assumption, the results from both seasons were combined to provide annual estimates.

The two seasons were considered as two crop activities in the TOA-MD model setup. Two sets of crop simulations were undertaken to address the core questions with the use of the climate projections from the five different GCMs.

These two crop simulations were for:

1. Current climate with current production system
2. Future climate with current production system

In addressing Question 1, the first and second simulation sets were compared (i.e., sensitivity analysis of climate change), without setting trends for prices/yields. Similarly for Question 2, the same set of simulations were undertaken with RAPs and trends for prices and yields. Trends for prices and yields were incorporated for Question 2 (impact of climate change on the future system). Trends for prices and yields were obtained from the IMPACT global economic model, with values specified for Sri Lanka (Group 1 in Table 5). We also did a sensitivity test with a second set of trend assessments (Group 2) derived largely from the IMPACT model to better understand the sensitivity to the choices in the RAPs.

Results

Climate results

The climate projections for the mid-century (2040–2069) for Batalagoda, based on 20 GCMs under higher greenhouse gas concentrations (RCP8.5) are shown in Fig. 3. There is a consistent rise in temperature in all 20 GCMs for both seasons. The increase in temperature is nearly consistent across all the months. For the Yala

Table 5. Values for trends for variables and indicators used in the TOA-MD that were obtained mostly from Groups 1 and 2.

Variable	Group 1-Trend factors mostly from RAPs		Group 2-Trend factors mostly from IMPACT global model	
	Description	Value	Description	Value
Yield trend τ	RAP defined value	1.25	AgMIP Reference scenario under IMPACT Global model	1.498
Price trend ϕ_1	AgMIP Reference price under IMPACT model	1.18	AgMIP Reference price trend under IMPACT Global model	1.179
Price trend ϕ_2	RAP defined value (assumed to be matched with cost trend)	1.2	SSP2_HGEM_DSSAT_5crop scenario price Trend under Impact Global model	1.462
Household size (HH)	RAP defined value (percentage decrease)	-16%	RAP defined value (percentage decrease)	-16%
Farm area (Ha)	RAP defined value (percentage decrease)	-18%	RAP defined value (percentage decrease)	-18%
Cost trend (ψ)	RAP defined value	1.2	Cost from IMPACT model (assumed to be same as SSP2_HGEM_DSSAT_5crop scenario price trend)	1.462
Non-agricultural income (Rs)	RAP defined value (percentage increase)	30%	RAP defined value (percentage increase)	30%

season, there is an increase in temperature ranging from 1.5 to 2.8°C and for the Maha season, there is an increase in temperature ranging from 1.1 to 2.4°C. The monthly climatology of rainfall in the future period shows a significant increase from September to November for all GCM scenarios and less change in other months.

A significance test was undertaken with a change of two standard deviations of yearly variation for either parameter taken as significant for the mean alone, and both mean- and variability-based scenarios (see Part 1, Chapter 3 in this volume). The results show that the temperature rise is significant in both scenarios for all GCM outputs for both Yala and Maha.

For Maha, there is an increase in average rainfall of up to 9.5 mm/day in the future period (with one GCM showing a drop of 0.1 mm/day) from a current average of 6 mm/day. This increase in rainfall is significant in both testing scenarios for both Yala and Maha, for 16 of the 20 GCM outputs including four of the five selected GCMs (except for HADGEM2-ES). Note this exceptional GCM was one of the warmest.

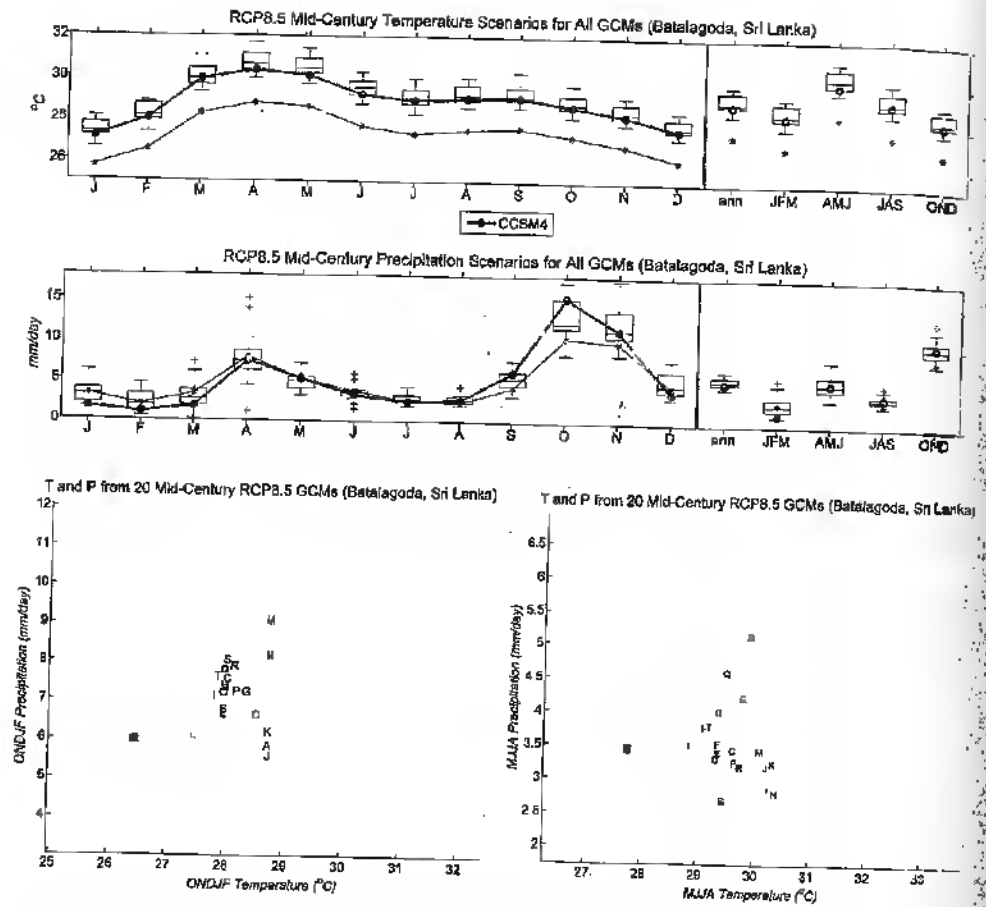


Fig. 3. Top left: The monthly and seasonal climatology for temperature in the present (1980–2010) as a solid line) and in the future projections (2040–2070 as box-and-whisker plots for the 20 GCMs) for Batalagoda in northwest Sri Lanka. The line shows the climatology for one GCM (CCM4) as an example. The letters indicate the respective GCMs and those selected for detailed analysis are shown in red. These are the GCMs CCSM4, GFDL-ESM2M, HadGEM2-ES, MIROC5, and MPI-ESM-MR and are labeled as E, I, K, O, and R. Top right: Shows the same but at the annual time-step (“ann”) and for the seasons of January to March (JFM), April to June (AMJ), July to September (JAS) and October to December (OND). These seasons approximately correspond to early and late Maha (October to March) and Yala (April to September) agricultural seasons. Second panel, left and right: The same as at the top but for precipitation rather than temperature. Third panel: The bottom graphic shows the “seasonally” averaged current (solid square) and future projections (letters as in top panel) and climate projections for the mid-century (2040–2069) under RCP8.5 for Batalagoda. The months in the season most likely to affect the rice crop are chosen — October to February for Maha and April to July for Yala.

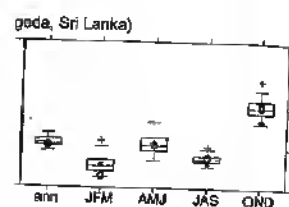
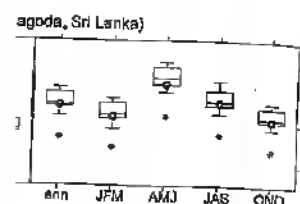
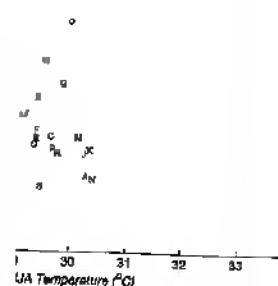


Figure 4. Simulated rainfall (mm) for the 20 GCMs (Batalagoda, Sri Lanka)



in the present (1980–2010) for one GCM (CCM4) as an detailed analysis are shown in the top panel) and climate scenario effects. The months in the season (left and right: The same as in top panel) and climate scenario effects. The months in the season (left and right: The same as in top panel) and climate scenario effects.

For the Yala season, there is an increase in rainfall of up to 2 mm/day for 10 of the GCMs and a decrease in rainfall for the rest of up to 1 mm/day from an average of 3.5 mm/day. However, only 10% of the GCMs showed a significant anomaly (a rise in this instance), and none of the five selected GCMs had a significant change in rainfall.

Crop modeling results

DSSAT-CERES calibration results

Simulated results with DSSAT-CERES for time taken to panicle initiation, anthesis, and maturity from emergence compared well with observed values for detailed and CRVTs experiments. RMSE (root mean square error) was around four to five days for all varieties (see Fig. 4 for calibration results of anthesis and yield for the Bg 300 cultivar). RMSE for yield was lower for the Bg 357 cultivar (425 kg/ha), compared to the other two varieties Bg 300 and Bg 358, which ranged from 1800 to 2000 kg/ha. All varieties had a similar RMSE of ~1400 for grain yield. Deviations for top weights and grain yields for these varieties compared to those observed were mainly due to biotic stress. For example, CRVTs of Bg 358 recorded lower observed yields due to a pest attack at grain-filling, which could not be controlled in time.

APSIM-ORYZA calibration results

The APSIM-ORYZA model calibration results (Fig. 4) showed a good fit, indicating RMSE for time taken to panicle initiation, anthesis, and maturity, were in the range of three to six days. RMSE for grain yield was around 1000 kg for Bg 300 and Bg 357, while it was higher (1200 kg) for Bg 358. Deviation of simulation for grain yields for these varieties compared to the observed was mainly associated with the biotic stress. For example, CRVTs of Bg 358 recorded lower observed yields due to a pest attack at grain-filling, which could not be controlled in time.

Crop simulation results for farm survey yields and climate scenario effects

Parallel studies were undertaken for two sets of locales chosen from the Kurunegala district as described in the methodology. Set 1 included farm survey data from Batalagoda, Nikaweratiya, and Rajanganaya and Set 2 included Migalewa and Kadawaramulla.

Crop simulations were generated using DSSAT and APSIM crop models. The same genetic coefficients as described above were used. Simulations for the base year (2012–2013), historical period (1980–2010), and five GCMs at mid-century

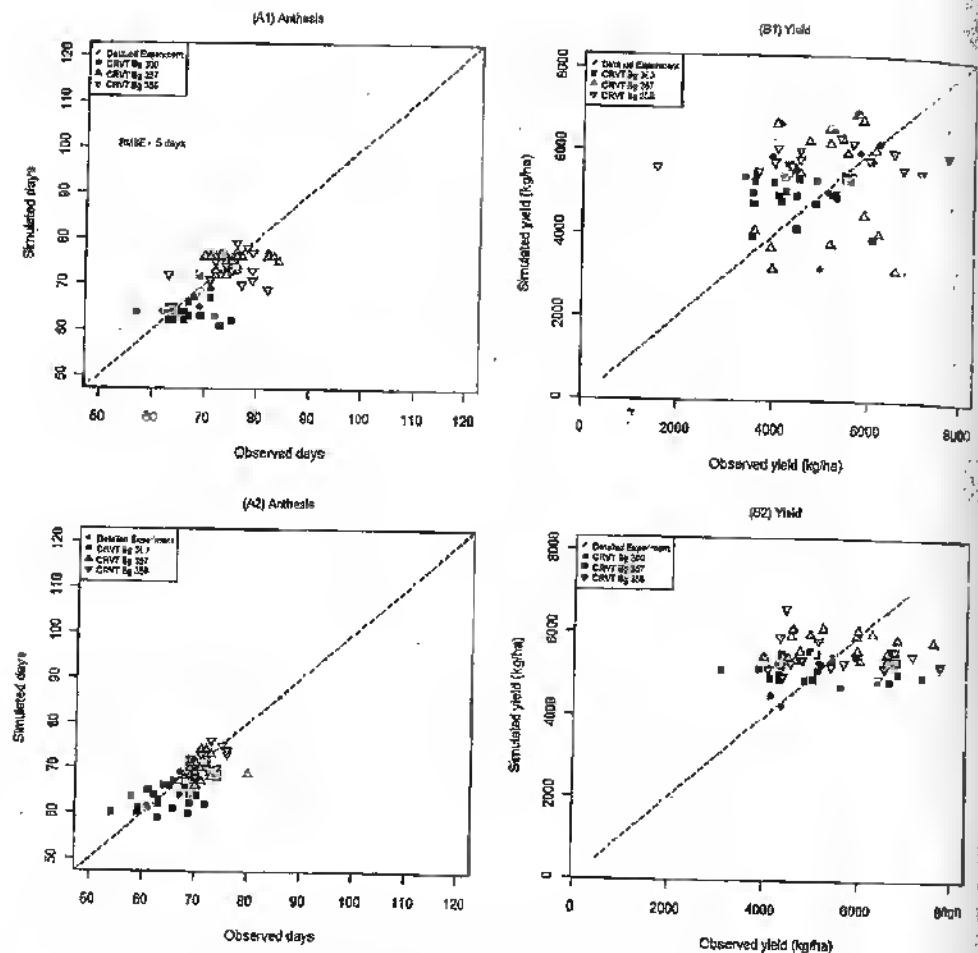
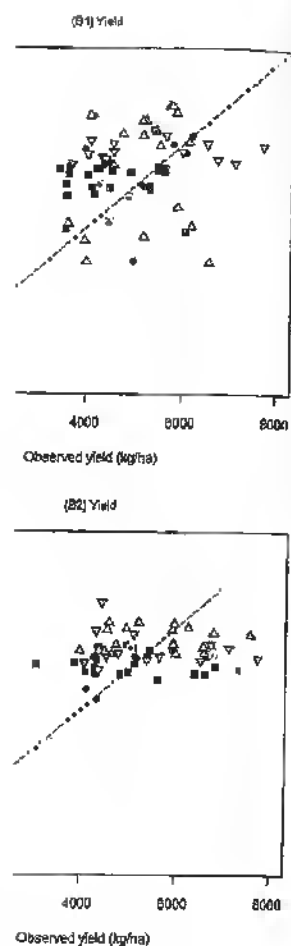


Fig. 4. Comparison between simulated and observed yields with a 1:1 line (---) of (A) days to anthesis and (B) grain yield for the rice variety Bg 300 using DSSAT (top row) and APSIM (bottom row).

(2040–2070) for the major and minor seasons were obtained. These results were calibrated and validated accordingly.

SET 1: Batalagoda, Nikaweratiya, and Rajanganaya

Simulation results for the first set (collection of all three locations) for the major and minor seasons of the base year (2012/2013) are presented in Fig. 5. Significant positive relationships were found between observed and simulated rice yields for both seasons for the DSSAT and APSIM crop models. A seasonal comparison revealed slightly greater overestimation for the minor season by DSSAT (RMSE of 1300 kg/ha) than for the major season (RMSE of 1200 kg/ha).



DSSAT-Major season: Kurunegala 2012/13

DSSAT-Minor season: Kurunegala 2012/13

APSIM-Major season: Kurunegala 2012/13

APSIM-Minor season: Kurunegala 2012/13

Fig. 5. Comparison between DSSAT-CERES simulated and observed yields of farmer fields in Kurunegala (Set 1) for the base year of (2012–2013) with a 1:1 line (---). This is shown for simulations from DSSAT in the top panel for the major (A1) and minor (B1) seasons. The results from APSIM-ORYZA simulations are shown in the bottom panel for the major (A2) and minor (B2) seasons.

However, APSIM simulated higher yields during the major season (RMSE of 1700 kg/ha) compared to the minor season (Fig. 5). Multi-model comparison of the probability of exceedance of simulated vs. observed yield revealed a more-or-less similar relationship between the two crop models for the minor season compared to the major season (Fig. 5).

Our simulations are undertaken with the assumption that the crop is not water-stressed. Water limitation for the rice crop is relatively lower in the major season than in the minor season. Sensitivity of these crop models to water status may have contributed to these differences. Farmer survey revealed that some farmers were

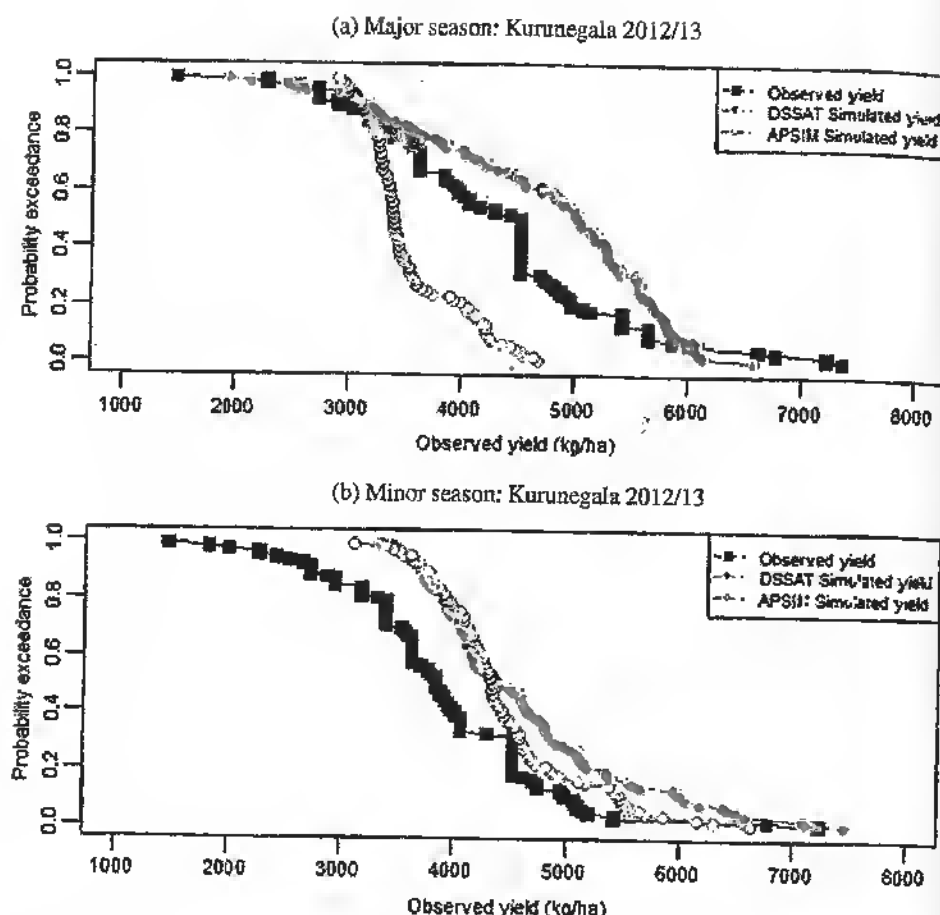


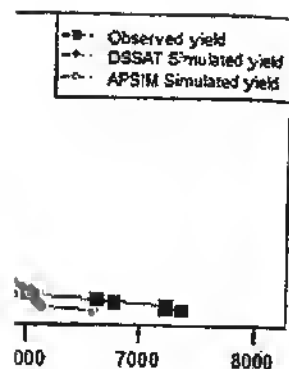
Fig. 6. The probability of exceedance yields for observed and simulated (DSSAT and APSIM) yield for farmer fields in Kurunegala for the base year (2012–2013) for the major (A — top) and the minor (B — bottom) seasons.

unable to get the required fertilizer at the correct time, and the application was delayed particularly in the minor season. Few farmers, especially in the Batalagoda region, also reported that their fields were infested with weeds that they were unable to control. These reasons may have also contributed to lower observed yield for some farmers, though the amount of fertilizer applied remained the same, resulting in higher simulated yields, RMSE, and poorer yield distribution fit for probability of exceedance in both crop models (Fig. 6).

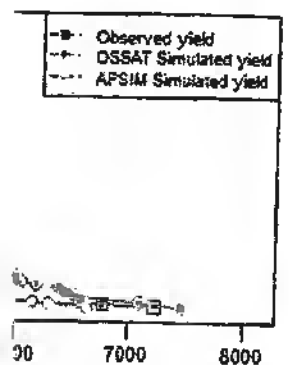
Yield prediction with DSSAT with GCM scenarios

DSSAT results revealed that rice yield is reduced for all GCMs with a different magnitude for each season (Fig. 7). Compared to the baseline period, percentage yield

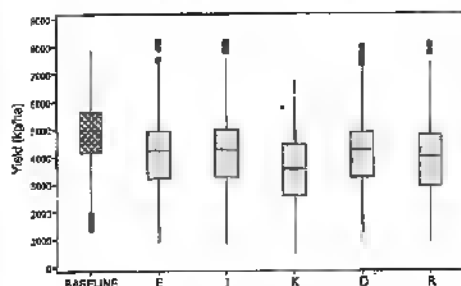
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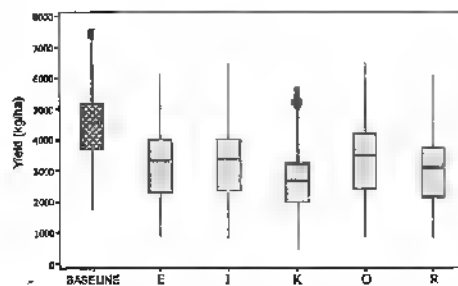
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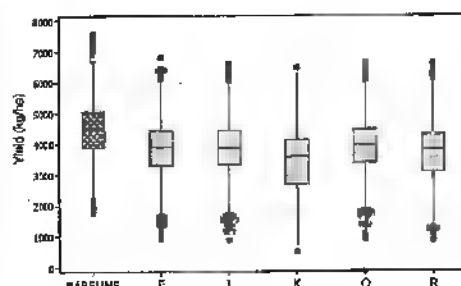
(a) DSSAT yield variations for major season in Kurunegala



(b) DSSAT yield variations for minor season in Kurunegala



(a) APSIM yield variations for major season in Kurunegala



(b) APSIM yield variations for minor season in Kurunegala

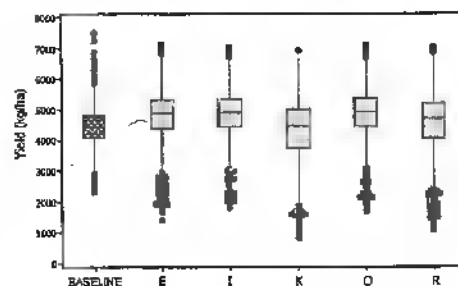


Fig. 7. Top: DSSAT simulated rice yield for the major (A) and minor (B) seasons for five GCMs (mid-century) compared to baseline period for farmer fields. Middle: As in top panel for APSIM simulated rice yield for the major (A) and minor (B) seasons. Bottom: As top for DSSAT simulated rice yield for the major (A) and minor (B).

reductions for the five GCMs CCSM4, GFDL-ESM2M, HadGEM2-ES, MIROC5, and MPI-ESM-MR (labelled E, I, K, O, and R) were 13, 12, 19, 15, and 16%, while percent reduction for the minor season was 27, 28, 41, 33, and 36%. The highest reduction was observed for the HadGEM2-ES (K) GCM for the minor season being the warmest of selected five GCMs. Since the Yala is the warmer season, it is likely that if temperature rises excessively, then the rice crop which is usually at its higher range of temperature tolerance (Weerakoon *et al.*, 2005) shall be adversely affected.

Yield prediction with APSIM with GCM scenarios

Different responses were observed for the climate change yield simulations with APSIM. Though a slight yield reduction was observed for all five GCMs in the major season, higher yields were simulated for four GCMs (except for the HadGEM2-ES GCM) in the minor season. Percentage yield reductions observed for the Maha season compared to the base period for the five GCMs (CCSM4, GFDL-ESM2M, HadGEM2-ES, MIROC5, and MPI-ESM-MR) were 5, 5, 8, 5, and 6% respectively while only 2% reduction was observed for the HadGEM2-ES GCM for

the Yala season. The other GCMs (E, I, O, and R) simulated 8%, 9%, 9%, and 3% greater yields respectively for the minor season, compared to the baseline period. In both seasons the highest yield reduction was observed for the HadGEM GCM.

SET 2: Kadawaramulla and Migalewa

Farmer-specific rice yields were simulated for Set 2 for the historical period and the projections of the five GCMs of mid-century (2050s) for the major and minor seasons using DSSAT and APSIM.

In the case of Kadawaramulla of Set 2, the rice cultivation was only available for the major season due to a devastating drought in the minor Yala season for which the field survey results are available. We were not able to obtain data for the minor season in years before or after as there is a system of irrigation being provided only on alternate years for this region. The results for Kadawarmulla are included in Zubair et al. (2014).

Results of the DSSAT simulations for the historical period of the major and minor seasons for the Migalewa location of Set 2 (Figs. 8 and 9) are qualitatively similar to that presented for Set 1. The RMSE of simulated yields is mostly the same (Fig. 8). The yield distribution as probability of exceedance matches well to the observed farm yield distribution (Fig. 9).

The yields simulated with DSSAT are reduced for all five GCMs for both major and minor seasons (Fig. 10). For Migalewa, the percentage yield losses in the major season compared to baseline for the five GCMs (CCSM4, GFDL-ESM2M, HadGEM2-ES, MIROC5, and MPI-ESM-MR) were 6.8, 6.1, 14.5, 7.5, and 7.9% respectively. Similarly for the minor season, the yield reduction was 24.8, 26.7, 36.8, 24.6, and 30.6% respectively. For Kadawaramulla yield reductions in the major

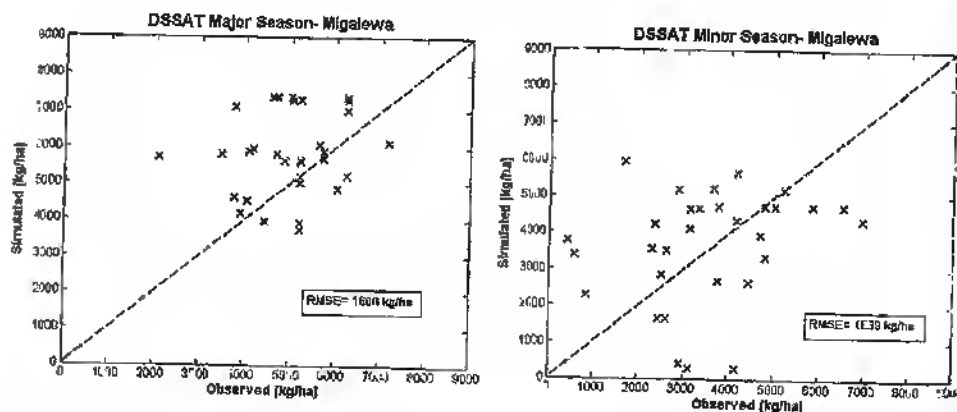


Fig. 8. Comparison between observed and DSSAT simulated yields for farmer fields in Migalewa (Set 1) for (left) major and (right) minor seasons for the base year (2012–2013) with a 1:1 line (---)

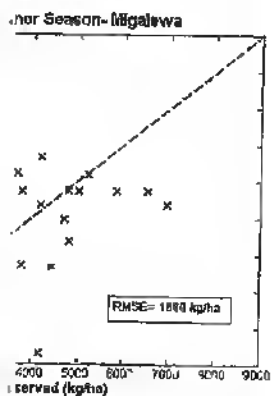
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farmer fields in Migalewa
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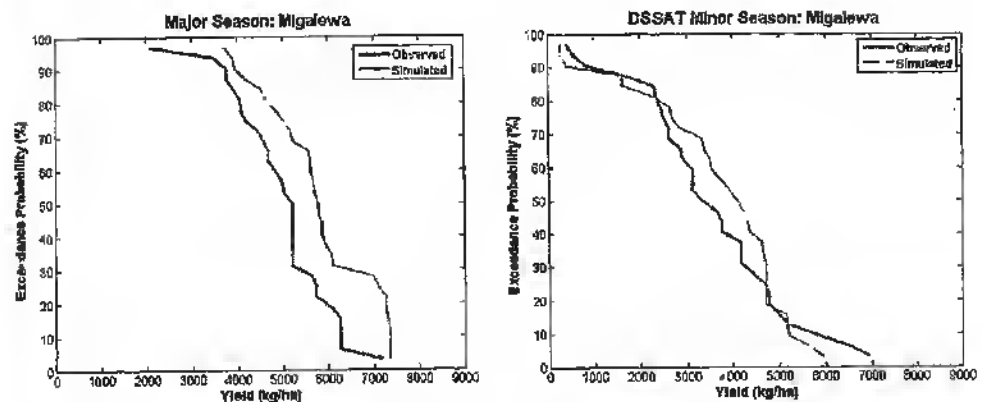


Fig. 9. The probability of exceedance of observed and simulated yields with DSSAT during the base year (2012–2013) in Migalewa for major and minor seasons.

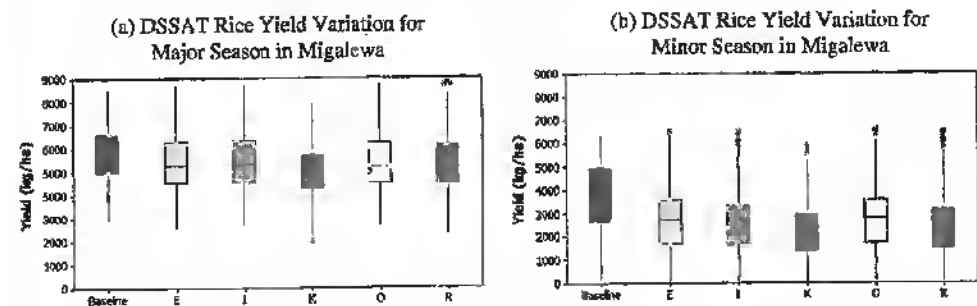


Fig. 10. DSSAT simulated rice yield for the major (A) and minor (B) seasons for five GCMs (mid-century) compared to baseline period for farmer fields Migalewa.

season were 3.1, 2.7, 9.8, 4.0, and 4.8%. The highest yield reductions were for simulations with GCM-HadGEM2-ES (Fig. 10).

Integrated Assessment Results

The results under Migalewa of Set 2 are presented under the integrated assessment section. The results from the TOA-MD analysis for Kadawaramulla are reported in Zubair *et al.* (2014) and Herath *et al.* (2013).

Addressing Core Question 1

With current agricultural systems and future climate: The projected climate change leads to a negative economic impact on 75–85% of farmers in Migalewa (Table 6). The percent of gains under all GCMs show similar results of approximately 13% of mean net returns. Net returns per farm decrease by 14–26% depending on the GCM

Table 6. TOA-MD analysis showing yields, net returns, *per capita* income, and poverty rate with and without climate change (top half labeled Question 1) and with climate change and changed agricultural practices (bottom half labeled Question 2) for Migalewa. The results are based on climate change as assessed from five selected GCMs CCSM4, GFDL-ESM2M, HadGEM2-ES, MIROC5, and MPI-ESM-MR (labeled E, I, K, O, and R) and trends as in Group 1.

	Stratum	GCM				
		E	I	K	O	R
Question 1	Observed mean yield (Rice-Activity1-Maha season) (Kg/Ha/Season)	4985	4985	4985	4985	4985
	Mean yield change (Rice) (%)	-7	-6	-15	-8	-8
	Observed mean yield (Rice-Activity2-Yala season) (Kg/Ha/Season)	3508	3508	3508	3508	3508
	Mean yield change (Rice) (%)	-25	-27	-37	-25	-31
	Losers (%)	76	78	85	77	80
	Gains (% mean net returns)	13	12	13	12	13
	Losses (% mean net returns)	-24	-25	-32	-24	-27
	Observed net returns without climate change (Rs/Farm/Year)	115777	115777	115777	115777	115777
	Observed net returns with climate change (Rs/Farm/Year)	98630	96632	86290	97697	94200
	Observed <i>per capita</i> income without climate change (Rs/Person/Year)	54256	54256	54256	54256	54256
	Observed <i>per capita</i> income with climate change (Rs/Person/Year)	49939	49436	46833	49704	48824
	Observed poverty rate without climate change (%)	55	55	55	55	55
	Observed poverty rate with climate change (%)	60	60	63	60	61
	Projected mean yield (Rice-Activity1-Maha season) (Kg/Ha/Season)	5830	5830	5830	5830	5830
Question 2	Mean yield change (Rice) (%)	-7	-6	-15	-8	-8
	Projected mean yield (Rice-Activity2-Yala season) (Kg/Ha/Season)	5399	5399	5399	5399	5399
	Mean yield change (Rice) (%)	-25	-27	-37	-25	-31
	Losers (%)	77	79	88	75	82
	Gains (% mean net returns)	10	10	10	11	10
	Losses (% mean net returns)	-20	-21	-29	-20	-23
	Projected net returns without climate change (Rs/Farm/Year)	163224	163224	163224	163224	163224
	Projected net returns with climate change (Rs/Farm/Year)	141487	138993	123907	143477	135253
	Projected <i>per capita</i> income without climate change (Rs/Person/Year)	87778	87778	87778	87778	87778
	Projected <i>per capita</i> income with climate change (Rs/Person/Year)	81263	80516	75995	81860	79395
	Projected poverty rate without climate change (%)	28	28	28	28	28
	Projected poverty rate with climate change (%)	31	32	35	31	33

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GEM2-ES, MIROC5, and

CM
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-15 -8 -8

508 3508 3508

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-32 -24 -27

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256 54256 54256

833 49704 48824

55 55 55

63 60 61

830 5830 5830

15 -8 -8

899 5399 5399

37 -25 -31

88 75 82

10 11 10

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24 163224 163224

07 143477 135253

78 87778 87778

95 81860 79395

28 28 28

35 31 33

projection. The HADGCM-ES2 (identified by K) leads to the most significant losses and net impacts. Poverty rates increases by 8–15% for the five GCMs. Poverty line was defined as those earning less than \$1.25/day. Highest poverty rate increase is shown under HADGCM-ES2 which has the highest temperature increase and the most yield drop. Note that the same rice prices are used for both System 1 and 2 with no trends used for yields and cost of cultivation. Hence analysis under Question 1 gives a basic assessment of the socio-economic impacts due to climate change.

Addressing Core Question 2

The impact of climate change on the future production system was assessed assuming that future production system will differ from current production system due to trends as described by the RAPs and the IMPACT global model and summarized in Group 1 in Table 5. The RAPs include an expectation of continuation of current development trends in the agriculture sector. The details of gains, losses, and net impacts are in Table 6 and in Fig. 11. We also assessed the sensitivity to the choices of RAPs by using trend factors (Group 2) taken largely from the IMPACT model.

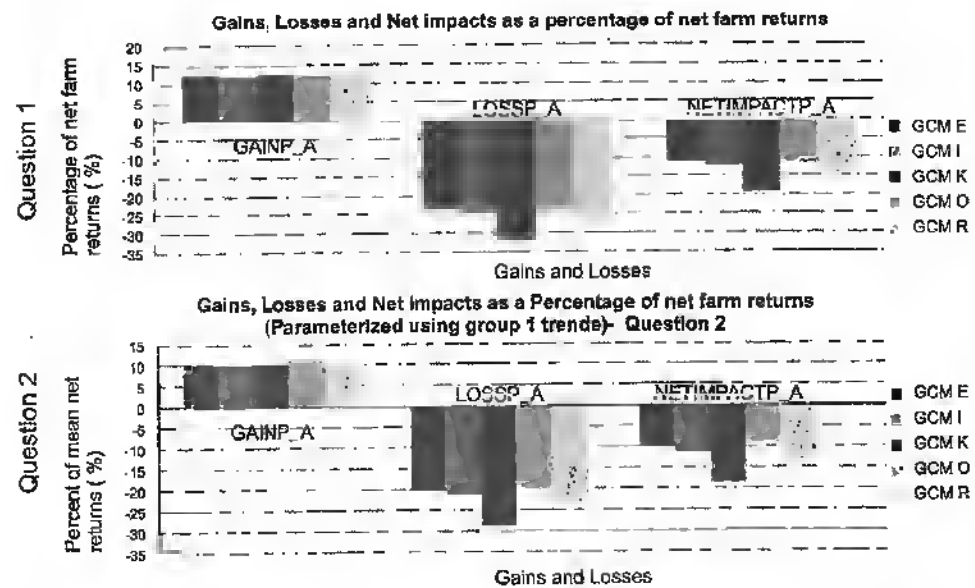


Fig. 11. The gains, losses and net impacts as a percentage of mean farm net returns for Migalewa as estimated by the TOA-MD analysis for Question 1 (top panel) of anticipated mid-century climate change and the current production system and Question 2 of anticipated mid-century climate change and future agricultural production system. The results are based on climate change as assessed inputs from five selected GCMs CCSM4, GFDL-ESM2M, HadGEM2-ES, MIROC5, and MPI-ESM-MR (labeled E, I, K, O, and R).

Table 7. As in bottom half for Table 6, addressing the impacts of climate change with future agricultural production system as comparison of results anticipated by the factors as given in Group 1 and Group 2 (see Table 5).

Variables	Group 1					Group 2				
	GCM E	GCM I	GCM K	GCM O	GCM R	GCM E	GCM I	GCM K	GCM O	GCM R
Losers (%)	77	79	88	77	82	37	41	67	39	48
Projected net returns without climate change (Rs/Farm/Year)	163224	163224	163224	163224	163224	193637	193637	193637	193637	193637
Projected net returns with climate change (Rs/Farm/Year)	141487	138993	123907	143477	135253	204520	200880	179096	202745	195497
Percentage change in projected net returns (%)	-13	-15	-24	-12	-17	6	4	8	5	1
Projected per capita income without climate change (Rs/Person/Year)	87778	87778	87778	87778	87778	96892	96892	96892	96892	96892
Projected per capita income with climate change (Rs/Person/Year)	81263	80516	75995	81860	79395	100154	99063	92535	99622	97450
Percentage change in per capita income (%)	-7	-8	-13	-7	-10	3	2	-4	3	1
Projected poverty rate without climate change (%)	28	28	28	28	28	23	23	23	23	23
Projected poverty rate with climate change (%)	31	32	35	31	33	22	22	25	22	23
Percentage change in poverty rate (%)	13	15	27	13	18	-7	-5	7	-6	-3

Climate change has a net negative economic impact on 76–88% of farmers with the future agricultural production system. The gains in the future under different GCMs range between 9.5 and 10% of mean farm returns (bottom left Fig. 11); losses range from 19 to 29% of mean farm returns). The losses under HADGCM-ES2 (GCM: K) are the highest. Net impact due to climate change would be negative for all GCM and losses shall range from 8–19% of net farm returns).

Poverty rate in the future production system without climate change is 27.8%. However poverty rates would increase with climate change by 12–26%. Poverty rates and *per capita* incomes under Question 2 have decreased in comparison to Question 1 (without climate change). The increase in off-farm income by 30% as anticipated under the RAPs has caused this decrease. The decrease in household sizes (by 16%) has also contributed to bringing down poverty rates.

Sensitivity analysis

To address the sensitivity of the TOA-MD results to the choice of future trends in the RAPs, we have redone the analysis with a different set of growth factors obtained mostly from the global IMPACT economic model (Group 2 in Table 5). Between Group 1 and 2, the trends for global prices, household size, farm area, and non-agricultural income were identical. There were significant differences in the trends for yield, local prices, and cost of production with the values in Group 2 being approximately about 15–20% greater. The results are shown in Table 7 and

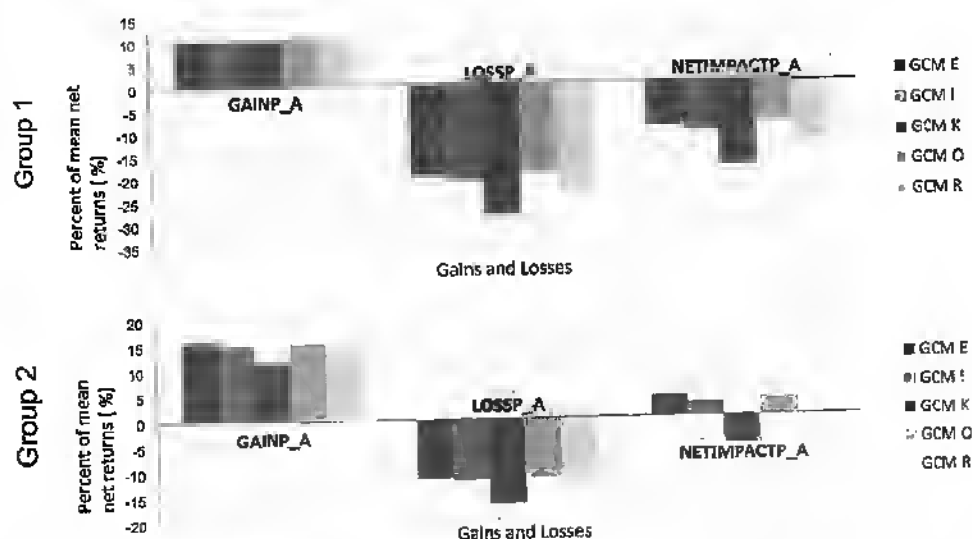


Fig. 12. Variation of gains, losses, and net impacts as a percentage of net farm returns for Question 2 utilizing Group 1 and 2 trends.

Fig. 12. Using the Group 2 trend values, the change in projected returns under climate change were actually more positive for four GCMs in contrast to the results with Group 1. Similarly the percentage change in *per capita* income was favorable for four GCMs under climate change, again in contrast to the results with trend factors from Group 1. These results show that the trend factors for yield, local prices and cost of production are critical. They also show the high sensitivity of the results to the input trend factors. Moreover the percentage of vulnerable farms (% of losers) is much lower under the Group 2 analysis compared to Group 1. This provides a confirmation that the choice of trend factors from global economic models and RAPs are likely to be one of the vital key elements in the process of designing adaptation strategies.

Conclusions and Discussion

A sustained program of research under AgMIP has led to the implementation of climate, crop, and economic models of rice agricultural systems in Sri Lanka.

Conclusions

Climate

The climate projections show a clear increase in temperature in the mid-20th century for a high greenhouse gas concentration pathway (RCP8.5); these models show a tendency towards a wetter future but there is scatter in these results. The results were largely consistent across five locations in Sri Lanka and the details are provided for data from the northwestern Province. The changes in the model output are described in terms of the Maha and Yala seasons next. The increase in average temperature for 2040–2070 from that of 1980–2010 ranged from 1.1–2.4°C for Maha and 1.5–2.8°C for Yala seasons. The rainfall shows a slight increase for a preponderance of the 20 GCMs in the CMIP5 archive, with the highest increase for October–November. During Maha, the average rainfall rises from a present average of 6 mm/day up to a future 9.5 mm/day for 19 of the models while it drops by 0.1 mm/day for one model. The magnitude of the rise was statistically significant for 16 of these models. During the Yala season, half of the models showed a decline in average rainfall of up to 1 mm/day from the normal of 2 mm/day, including four of five selected GCM outputs and 10 of the other models showed an increase — this increase was statistically significant for these ten models.

Crop

Genetic coefficients for the DSSAT and APSIM rice models, which were generated with Set 1 data, are presented here. Genetic coefficients obtained independently with a subset of data are presented in Zubair *et al.* (2014) and are similar.

Simulations were undertaken for farmer fields with Set 1 and Set 2 of data with DSSAT and APSIM rice models and the DSSAT results are presented for both sets. These simulations showed an adequate match of the probability of exceedance in the case of DSSAT for both sets while the estimates from the APSIM models were lower.

Under the projected climate change, the simulations using DSSAT with climate change scenarios projected relative yields that were lower for the Maha season (by 6–19% for Set 1 and 6–15% for Set 2) and for the Yala season (24–41% for Set 1 and 25–37% for Set 2).

Crop simulations from DSSAT and APSIM with Set 1 showed contrasting results. The comparison of simulated and observed yields for the farmer fields in Set 1 showed a lower RMSE with DSSAT than APSIM for Maha but not for Yala. Simulated yields showed yield drops for the future—12–19% for Maha and 27–41% for Yala.

The adverse effects were more pronounced for the Yala season. The GCM with the highest temperature increase — HadGEM2-ES — showed the highest yield drop — 41% for Yala.

Integrated assessment

The TOA-MD economic model was used to assess the socio-economic impacts on paddy farmers due to climate change. The projected climate change brings losses for most farmers (ranging from 75–85% losers depending on the GCMs) for Migalewa. TOA-MD results for the GCM with the highest temperature increase (HadGEM2-ES) showed the lowest yields and highest economic impacts with 85% losers.

The impact of climate change on the future production system was assessed (Question 2) assuming that future production system will differ from current production system due to continuation of current development trends in the agriculture sector. Considering such trends along with climate change leads to a simulated 77–88% losers in Migalewa.

The results were sensitive to the choices in parameter trends obtained from the RAPs and the ones obtained from IMPACT. This has important implications for the design and implementation of policies and adaptation strategies based on the analysis of possible future impacts of climate change. More work is needed to understand better the effects of technology and price trends as a result of global economic models or other projections.

Discussion

Climate

The future projections for temperature reported here are consistent with past IPCC projections for South Asia (IPCC, 2007). The IPCC Fifth Assessment Report (AR5)

anticipates an increase in temperature of 2.4 to 2.6°C in the global average for RCP2.6 for 2046–2065 and an increase in annual rainfall of up to 10% for 2081–2100 (IPCC, 2013).

There has been a multiplicity of downscaled climate projections for Sri Lanka based on assessments prior to AR5 which was reviewed by Eriyagama and Smakthin, (2010). These projections agree reasonably among themselves on projections for temperature and disagree widely among themselves for projections of precipitation. The contribution of this work is to undertake assessments with the entire ensemble of CMIP5 models and present the ensemble of results, which also includes uncertainty among model implementations.

While this work provides for uncertainty among the climate models, we do need to address the larger issue of how well the models perform in this region, the small spatial scales that we consider, and the robustness of the models as they take on different regimes in the climate system. The climate models as implemented also do not provide a basis for future changes in extreme events. These are issues that could be better answered in the future and should be considered in the interpretation of implications for policymaking.

In the recent decades, there has been a tendency towards drying conditions in the study region and in Sri Lanka generally. Such a trend has not been captured by models in the past. This phenomenon of near-term climate change needs to be addressed in the future. Thus the paradox of the recent drying trend alongside projections of wetting needs to be addressed.

Crop

We have assessed the sensitivity of rice yield with temperature, CO₂, and rainfall by varying each of these parameters individually in the anticipated range of changes with a DSSAT crop model implementation with Set 1 (Zubair *et al.*, 2014). The model shows very little sensitivity to changes in rainfall, and modest sensitivity to CO₂, but high sensitivity to changes in temperature. These results are consistent with past work that shows that rice yields are expected to increase with elevated CO₂ levels and decline with increases in temperature (Wassmann and Dobermann, 2007) but provide specific quantitative details for our model implementation in Zubair *et al.* (2014).

The effects of pests and diseases on paddy production can override some of the projections and thus need to be taken account of in the future. The role of rising salinity will have to be considered in the coastal areas that are vulnerable to salt water intrusion into groundwater associated with sea level rise.

There is a need to implement modules and test their implementation to take better account of water stress in the rice crop models as we use these models for relatively drier areas with limited irrigation in Sri Lanka.

There is a range of climates even within the rice-growing areas of Sri Lanka, which includes warmer, colder, drier, and wetter climates, and other soil types and associated agricultural practices for which the crop models should be further tested. One could also take advantage of practices in locations that may have a present climate similar to a projected future climate elsewhere.

Integrated assessment

In the RAPs that we used, the future agricultural practices help improve rice productivity trends and help mitigate the negative impacts of climate change on agricultural systems. Any RAP is only representative and other choices should be considered. The results from the TOA-MD model are highly dependent on the crop model simulations and on model implementation.

Any biases in the crop simulations would affect the TOA-MD results significantly. The samples used to parameterize the model are fairly small under this study. In the future, the crop and economic models shall be implemented for other sites where we already have survey results.

Our analysis points to the likelihood of inadequate income stability of farming and this can cause farmers to look for other employment options. Increase in off-farm employment under the RAP could have been one of the factors leading to this outcome. However this could pose a serious threat to rice production and will need to be addressed.

An aggregate study (Seo *et al.*, 2005) to assess climate change impacts on agriculture in Sri Lanka show that impacts due to climate change could vary from -11 billion rupees to +39 billion rupees nationally depending on the climate scenario (Seo *et al.*, 2005). This work has provided for economic impacts on a much finer scale, taking better account of local conditions. Although one may say that there is general agreement with our work, the state of such studies are preliminary and highly dependent on future projections, methodology, and future agricultural pathways.

Adaptation measures

The adaptation strategies that were described in the first section of this chapter are aimed to deal with three important issues. Coping with extreme risks for farmers, varietal improvement, and coping with water scarcity. An extension to the current analysis will be to assess the impacts of those adaptation strategies on the agricultural production system of Migalawa.

Farmer risk reduction and risk transfer

Both our surveys of farmers and work with the economic analysis highlighted the need for better management of risks that farmers face. Better weather- and

climate-based hazard predictions, predictions for water availability, market-based risk predictions, the use of risk transfer mechanisms such as insurance and farming cooperatives, and better implementation of guaranteed price schemes shall have to be prioritized if there is a policy priority for sustaining the number of rice farmers in Sri Lanka.

Changes in varietal use and varietal improvement

There is significant variation of climate in Sri Lanka and agricultural practices. Thus as climate changes it may still be possible that varieties adapted to other regions become better suited for a given region. Such an analysis of climate shall point to some options for varietal adoption. Further analysis of data from varietal trials may help. In addition, there is an ongoing program of varietal improvement in Sri Lanka which may be critical as climate changes. The adoption of varieties that have enhanced flood, drought, salinity, and disease tolerance as the climate and soil conditions change may be critical to tolerant rice varieties.

Water management

Our work here has been with assumptions of perfect irrigation. However as seen in Kadawaramulla, drought and irrigation failures are critical. Moreover, there is increasing likelihood of diversion of water for urban use and other purposes (Zubair et al., 2014). Thus greater attention shall have to be paid to assessing the risk of water scarcity in the future in agricultural areas, the risks in ensuring adequate irrigation, and the use of water conservation techniques.

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References

- Amarasinghe, U. A., Mutuwatta L., and Sakthivadivel, R. (1999). Water scarcity variations within a country: a case study of Sri Lanka, International Water Management Institute, Research Report 32, Colombo, Sri Lanka.
- Antle, J. M. (2011). Parsimonious Multi-Dimensional Impact Assessment, *American Journal of Agricultural Economics*, 93(5), 1292–1311.
- Antle, J. M. and Valdivia, R. O. (2006). Modelling the supply of ecosystem services from agriculture: A minimum-data approach, *Australian Journal of Agricultural and Resource Economics*, 50, 1–15.
- Central Bank of Sri Lanka (2013). *Economic and Social Statistics of Sri Lanka*, Central Bank, Colombo, Sri Lanka.
- Climate Change Secretariat (2010). *National Climate Change Adaptation Strategy for Sri Lanka 2011 to 2016*, Climate Change Secretariat, Sri Lanka Ministry of Environment, Colombo.
- De Costa, W. A. J. M., Weerakoon, W. M. W., Chinthaka, K. G. R., Herath, H. M. L. K., and Abeywardena, R. M. I. (2007). Genotypic variation in the response of rice (*Oryza sativa* L.) to increased atmospheric carbon dioxide and its physiological basis, *Journal of Agronomy and Crop Science*, 193(2), 117–130.
- Department of Agriculture (2009). *Paddy Statistics of Sri Lanka*, Department of Agriculture Press, Gannoruwa, Sri Lanka.
- Department of Agriculture (2010). *Agriculture Statistics of Sri Lanka*, Department of Census and Statistics, Department of Agriculture Press, Gannoruwa, Sri Lanka.
- Department of Census and Statistics. (2012a). *Small Holding Sector. Census of Agriculture-2002*, Department of Census and Statistics Press, Colombo, Sri Lanka.
- Department of Census and Statistics (2012b). *Census of Population and Housing*, Department of Census and Statistics Press, Colombo, Sri Lanka.
- Dharmarathna, W. R. S. S., Herath, S., and Weerakoon, S. B. (2014). Changing the planting date as a climate change adaptation strategy for rice production in Kurunegala district, Sri Lanka, *Sustainability Science*, 9(1), 103–111.
- Eriyagama, N. and Smakhin, V. (2010). "Observed and Projected Climatic Changes, Their Impacts and Adaptation Options for Sri Lanka: A Review", in *Proceedings of the National Conference on Water, Food Security and Climate Change in Sri Lanka*, Volume 2, International Water Management Institute, Colombo pp. 99–117.
- Gadgil, S., Rajeevan, M., Zubair, L., and Yadav P. (2011). "South Asian Monsoon: Inter Annual Variability", in Chang, C., Ding, Y., Lau, N., Johnson, R. H., Wang, B., and Yasunari, T. (eds.), *Global Monsoon System, Research and Forecast*, World Scientific Publishing Company, Singapore.
- Herath, D., De Alwis, A. E. N., Agalawatte, A. S. M. P. M. B., Harischandra, Y. G., Chandrasekara, S. S. K., Yahiya, Z., Zubair, L., and Samarasinghe, P. A. (2013). "Simulating Socio Economic Impacts of Climate change on Rice Farming Systems: Trialing a Novel Integrated Methodology for Kadawaramulla, Kurunegala", in *Proceedings of the University of Peradeniya Economics Research Symposium (PERS) 2013*, University of Peradeniya, pp. 38–42.
- Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., and Jarvis, A. (2005). Very high resolution interpolated climate surfaces for global land areas, *International Journal of Climatology*, 25, 1965–1978.
- Hoogenboom, G., Jones, J. W., Wilkens, P. W., Porter, C. H., Boote, K. J., Hunt, L. A., Singh, U., Lizaso, J. L., White, J. W., Uryasev, O., Royce, F. S., Ogoshi, R., Gijsman, A. J., Tsuji, G. Y., and Koo, J. (2012). *Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.5* [CD-ROM], University of Hawaii, Honolulu, Hawaii.

- IPCC (2007). Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L. (eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC*, Cambridge University Press, Cambridge.
- IPCC (2013). Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M. (eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, p. 1535.
- Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J., and Ritchie, J. T. (2003). The DSSAT cropping system model, *Eur. J. Agron.*, 18(3), 235–265.
- Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., Huth, N. I., Hargreaves, J. N. G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J. P., Silburn, M., Wang, E., Brown, S., Bristow, K. L., Asseng, S., Chapman, S., McCron, R. L., Freebairn, D. M., and Smith, C. J. (2003). An overview of APSIM, a model designed for farming systems simulation, *Eur. J. Agron.*, 18(3) 267–288.
- Kurukulasuriya, P. and Ajwad, M. I. (2007). Application of the Ricardian technique to estimate the impact of climate change on smallholder farming in Sri Lanka, *Climatic Change*, 81(1), 39–59.
- Lyon, B., Zubair, L., Ralapanawe, V., and Yahya, Z. (2009). Fine scale evaluation of drought hazard for tropical climates, *Journal of Applied Meteorology and Climatology*, 48(1), 77–88.
- Mahanama, S. P. P. and Zubair, L. (2011). Production of streamflow estimates for the Climate Change Impacts on Seasonally and Intermittently Open Tidal inlets (CC-SIOT) Project, FBCT Technical Report 2011-01, Foundation for Environment, Climate and Technology, Digana Village.
- Mapa R. B., Dassanayake A. R., and Nayakekorale, H. B. (2005). Soils of the Intermediate Zone of Sri Lanka: Morphology, Characterization and Classification, Special publication No. 4. Soil Science Society of Sri Lanka, Peradeniya.
- Matthews, R. and Wassmann, R. (2003). Modelling the impacts of climate change and methane emission reductions on rice production: A review, *European Journal of Agronomy*, 19(4), 573–598.
- Ministry of Agricultural Development and Agrarian Services (2008). "Let us cultivate and uplift the nation", National campaign to motivate domestic food production 2008–2010, Ministry of Agricultural Development and Agrarian Services of Sri Lanka, Colombo.
- Ministry of Agriculture Development and Agrarian Services. (2007). *National Agricultural policy for Sri Lanka*. Available at: <http://www.agrimin.gov.lk/web/images/docs/1277294350B%20NATIONAL%20AGRICULTURAL%20POLICY.pdf>. Accessed on 28 September 2014.
- Ministry of Environment (2000). *National Report on Desertification/Land Degradation in Sri Lanka*. Available at http://www.unccd.int/regionalreports/sri_lanka-eng2000.pdf. Accessed on 28 February 2014.
- Climate Change Secretariat (2010). *National climate change adaptation strategy for Sri Lanka. 2011–2016*, Climate Change Secretariat, Ministry of Environment, Colombo, Sri Lanka.
- Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., and Wilbanks, T. J. (2010). The next generation of scenarios for climate change research and assessment, *Nature*, 463(7282), 747–756.
- Pain, A. (1986). "Agricultural Research in Sri Lanka: An Historical Account", in *Modern Asian Studies*. Cambridge University Press, Cambridge, 20(4):755–778.
- Punyawardena, B. V. R. and De Silva, R. P. (2011). *Drought Risk Profile of Sri Lanka*, Disaster Management Center, Sri Lanka.
- Raby, N. and Merrey, D. (1989). *Professional Management in Irrigation Systems: A Case Study of Performance Control in Mahaweli System H Sri Lanka*. Available at: <http://pdf.usaid.gov/pdf/docs/PNABGI69.pdf>. Accessed on 19 October 2014.

- , Averyt, K. B., Tignor, M., *Science Basis. Contribution of* Cambridge University Press.
- K., Boschung, J., Nauels, A., *The Physical Science Basis* the Intergovernmental Panel 535.
- D., Hunt, L. A., Wilkens, P., AT cropping system model.
- son, M. J., Holzworth, D., ean, G., Verburg, K., Snow, ., Asseng, S., Chapman, S., erview of APSIM, a model 1–288.
- n technique to estimate the *natic Change*, 81(1), 39–59.
- valuation of drought hazard *logy*, 48(1), 77–88.
- ates for the Climate Change (T) Project, FECT Technical dlogy, Digana Village.
- of the Intermediate Zone of ial publication No. 4, Soil
- : change and methane emis- *Agronomy*, 19(4), 573–598.
- t us cultivate and uplift the n 2008–2010, Ministry of ombo.
- National Agricultural pol- ages/docs/1277294350E%* on 28 September 2014.
- Land Degradation in Sri eng2000.pdf*. Accessed on
- ategy for Sri Lanka. 2011– bo*, Sri Lanka.
- van Vuuren, D. P., Carter, T. B., Nakicenovic, N., Riahi, Wilbanks, T. J. (2010). The sment, *Nature*, 463(7282),
- ”, in *Modern Asian Studies*,
- file of Sri Lanka*, Disaster
- Systems: A Case Study of* t: <http://pdf.usaid.gov/pdf>.
- Rienecker, M. M., Suarez, M. J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M. G., Schubert, S. D., Takacs, L., Kim, G. K., Bloom, S., Chen, J. Y., Collins, D., Conaty, A., da Silva, A., Gu, W., Joiner, J., Koster, R. D., Lucchesi, R., Molod, A., Owens, T., Pawson, S., Pegion, P., Redder, C. R., Reichle, R., Robertson, F. R., Ruddick, A. G., Sienkiewicz, M., and Woollen, J. (2011). MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications, *J. Clim.*, 24(14), 3624–3648.
- Rosenzweig, C., Jones, J. W., Hatfield, J. L., Muttter, C. Z., Adiku, S. G. K., Ahmad, A., Beletse, Y., Gangwar, B., Guntuku, D., Kihara, J., Masikati, P., Paramasivan, P., Rao, K. P. C., and Zubair, L. (2012). “The Agricultural Model Intercomparison and Improvement Project (AgMIP): Integrated regional assessment projects”, in Hillel, D. and Rosenzweig, C. (eds.), *Handbook of Climate Change and Agroecosystems: Global and Regional Aspects and Implications*, Imperial College Press, London, pp. 263–280.
- Rosenzweig, C., Jones, J. W., Hatfield, J. L., Antle, J. M., Boote, K. J., Thorburn, P., and Valdivia, R. O. (2013a). *AgMIP Guide for Regional Integrated Assessments: Handbook of Methods and Procedures Version 5.1*. Available at: <http://www.agmip.org/wp-content/uploads/2014/07/AgMIP-Regional-Integrated-Assessment-Handbook-v5.1.pdf>. Accessed on 21 March 2014.
- Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., Boote, K. J., Thorburn, P., Antle, J. M., Nelson, G. C., Porter, C., Janssen, S., Asseng, S., Basso, B., Ewert, F., Wallach, D., Baigorría, G., and Winter, J. M. (2013b). Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies, *Agric. Forest Meteorol.*, 170, 166–182.
- Ruane, A. C., Goldberg, R. and Chrysanthacopoulos, J. (2014). Climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation, *Agr. Forest Meteorol.*, 200. doi: 10.1016/j.agr.formet.2014.09.016.
- Samuel, T. D. M. A. (1991). Estimation of global radiation for Sri Lanka, *Solar Energy*, 47, 333–337.
- Sangakkara, U. R. and Nissanka, S. P. (2008). Food security in Sri Lanka — Agronomic Implications and Potentials, *Journal of National Science Foundation Sri Lanka*, 36(2), 17–24.
- Seo, S. N. N., Mendelsohn, R., and Munasinghe, M. (2005). Climate change and agriculture in Sri Lanka: A Ricardian valuation, *Environment and Development Economics*, 10, 581–596.
- Taylor, K. E., Stouffer, R. J., and Gerald, A. M. (2012). An overview of CMIP5 and the experiment design, *Bulletin of the American Meteorological Society*, 93(4), 485–498.
- Wassmann, R. and Dobermann, A. (2007). Climate change adaptation through rice production in regions with high poverty levels, *Journal of Semi-Arid Tropical Agricultural Research*, 4(1).
- Weerakoon, W. M. W., De Costa, W. A. J. M., and Abey Siriwardena, D. S. de Z. (2005). Physiological responses of indica rice varieties to increased atmospheric CO₂ and temperature, *Journal of Agricultural Meteorology*, 60, 601–604.
- Wickremasinghe, S. T. (2006). Development of the national agricultural research system (NARS) in Sri Lanka with special reference to food crops sub sector: Issues related to science policy, *Journal of National Science Foundation Sri Lanka*, 34(2), 69–83.
- Wilby, R. L., Charles, S. P., Zorita, E., Timbal, B., Whetton, P., and Mearns, L. O. (2004). *Guidelines for use of climate scenarios developed from statistical downscaling methods*. Available at: <http://www.narccap.ucar.edu/doc/tgca-guidance-2004.pdf>. Accessed on 14 October 2014.
- Yahiya, Z., Adhikari, S., Weerasekara, M., and Zubair, L. (2011). The Impacts of El Niño Southern Oscillation (ENSO) Events on Rice Production, Area and Yield in Sri Lanka, FAO/SEARCA Project. FECT Technical Report 2010-01, Foundation for Environment, Climate and Technology, Digana Village.
- Zubair, L. (2002). El-Niño-Southern Oscillation influences on Rice Production in Sri Lanka, *International Journal of Climatology*, 22, 249–260.
- Zubair, L. (2004). *Weather and Climate in Sri Lanka: A Reference Guide*, Natural Resources Management Services, Kandy, Sri Lanka.

- Zubair, L. (2005). Modernization of Sri Lanka's Traditional Irrigation System and Sustainability. *Science, Technology and Society*, 10(20), 161-195.
- Zubair, L., R. Perera and Z. Yahya. (2005). Was the 2002/03 Maha bumper harvest due to El Nino? *Journal of the Institute of Engineers*, 4, 63-70.
- Zubair, L. and C.F. Ropelewski. (2006). The strengthening relationship of ENSO and the North-East Monsoon rainfall over Sri Lanka and Southern India, *Journal of Climate*, 19(8), 1567.
- Zubair, L., Nissanka, S. P., Weerasinghe, K. D. N., Punyawardhene, B. V. R., Weerakoon, W. M. W., Wickramagamage, P., Agalawatte, P., Chandrasekera, S. C., Delpitiya, P., Navaratne, C. M., Gunaratna, J., Herath, D. I., Herath, R. M., Karunaratne, A., Ratnayake, S., Samarasinghe, P., Sammuganathan, K., Vishwanathan, J., Wijekoon, E., Weerasinghe, A. K., Yahya, Z., Perera, T. M. R. S., Gunasekara, A. A. I., Ratnasekera, H., Ralapanawe, V., Seneviratne, G., and Wallach, D. (2014). Modeling the impacts of a variable and changing climate on rice agricultural systems in Sri Lanka for AgMIP. Sri Lanka Project Final Report for AgMIP, Technical Report, Foundation for Environment, Climate and Technology, Kandy, Sri Lanka.